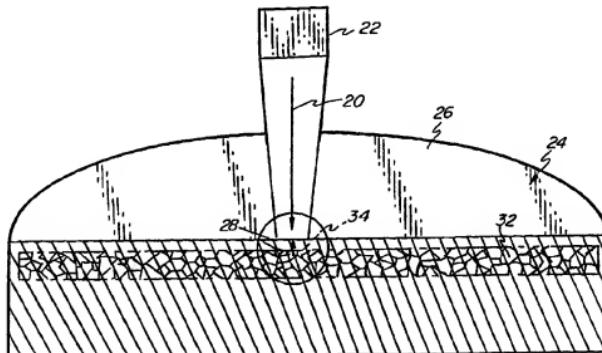




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(54) Title: METHOD OF ULTRASONIC ON-LINE TEXTURE CHARACTERIZATION



(57) Abstract

A sputtering target (24) under test is irradiated with an ultrasonic pulse (20). The ultrasonic pulse (20) has a wavelength in the sputtering target (24) in the range of the average grain size for the target (24) under test. Backscattering echoes (28) are produced by the interaction of the pulse (20) with grain boundaries in the target (24) under test. The backscattering echoes (28) are detected and a representative electrical signal is generated. The number of occurrences of the backscattering echoes (28) having amplitudes within predetermined ranges are determined. A histogram of the number of occurrences versus amplitude is plotted. The histogram for the target (24) under test is compared with reference histograms for sputtering targets having known crystallographic orientations to determine the texture of the target (24) under test.

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METHOD OF ULTRASONIC ON-LINE TEXTURE CHARACTERIZATION

BACKGROUND OF THE INVENTION

This invention relates to a non-destructive testing method for
5 determining the texture of materials using ultrasonics.

The word "texture" designates direction-dependent properties of
materials. One direction-dependent property of particular interest is elastic
anisotropy in polycrystalline materials that results from the non-random distribution
of the crystallographic orientations of single grains. Crystallographic texture is
10 described by an orientation distribution function (ODF). Information on ODF is
usually obtained from pole figure X-ray diffraction and typically consists of
thousands of diffraction data points.

Conventional texture analysis of materials normally involves
destructive testing. A small sample is cut off from a material and tested in a
15 laboratory. In some cases, especially in production control, it is not necessary to
determine the "whole" texture. In this case, it is possible to use a low-resolution
texture analysis method which relies upon a strict correlation between some material
physical properties such as, for example, elastic or magnetic properties, and
crystallographic texture. By restricting the texture analysis to a low-resolution
20 technique, it is possible to perform texture analysis in a non-destructive way that
offers the possibility of on-line quality control inspection.

Three different techniques for low-resolution texture analysis are
known. A first technique consists of taking X-ray measurements of a material under
test. A device, called an "On-Line Texture Analyzer", designed and used for this
25 purpose, irradiates a sample with an incident beam containing a continuous spectrum
of wavelengths such as, for example, the X-ray bremsstrahlung spectrum.
Characteristic pole-intensities of the sample are measured by energy-dispersive
detectors detecting the X-ray bremsstrahlung spectrum transmitted through the
sample material. However, this technique is limited to relatively small thicknesses of
30 material. This limitation is due to strong X-ray attenuation and dispersion inside the
polycrystalline material, and strict requirements for positioning of the X-ray source
and detectors with respect to the texture of the material sample.

A second technique consists of electromagnetic Barkhausen noise and dynamic magnetostriction measurements. However, this technique is limited to materials having strong magnetic anisotropy.

A third technique is based on the measurement of a material's

5 vibrational properties, such as an ultrasound velocity, which are known to be correlated with the material texture. Ultrasound velocity measurements have advantages over the first two techniques in that samples to be tested are not limited in thickness, and materials without strong magnetic anisotropy may be analyzed.

A prior art ultrasonic method for low-resolution texture analysis of

10 single-phase polycrystalline materials such as, for example, low-alloyed aluminum having a cubic structure and orthorhombic texture is depicted in Figure 1. This technique employs a pulse-echo method to determine three ultrasound absolute propagation velocities (with respect to the specimen coordinate system) propagating in the rolling, transverse, and normal directions.

15 A single, short-duration, high-frequency ultrasound pulse 10, generated by an ultrasonic transducer 12, advances into a specimen 14 which has flat, parallel surfaces. Multiple reflections of ultrasound inside the specimen 14 results. A series of consecutive echos 16 (see Fig. 1A) with gradually decreasing amplitudes are generated. The echos 16 are received by the transducer 12 for calculation of the

20 propagation velocity. The propagation velocity may be calculated using measurements of ultrasound round-trip path length and ultrasound round-trip time-of-flight. The round-trip path length may be determined as a doubled specimen thickness (L in Fig. 1) precisely measured in the direction of ultrasound propagation. The ultrasound time-of-flight may be measured as a time interval or period 17

25 between the leading edges of two consecutive echos 16. The absolute propagation velocities, calculated as a ratio of round-trip path length to time-of-flight, are usually used to determine the elastic constants (fourth-order expansion coefficients of the elasticity matrix) which characterize the texture of the specimen 14.

30 However, the accuracy of time-of-flight measurements may vary substantially depending on a number of factors such as: ultrasound pulse frequency spectrum; pulse rise time, length and shape; transducer-to-specimen positioning and coupling; and frequency band, resolution, and accuracy of the electronic receiving system. The accuracy of the time-of-flight measurements is especially critical for

materials having a low elastic anisotropy factor such as, for example, low-alloyed aluminum. In order to obtain acceptable measurement accuracy, out-of-line laboratory measurements may be required. The prior art ultrasonic method for texture characterization may not be suitable for on-line texture analysis.

5

SUMMARY OF THE INVENTION

A method of on-line ultrasonic texture characterization of a sputtering target is provided. Texture characterization may be accomplished through analysis of an ultrasonic backscattering signal amplitude distribution. A broad-band, focused 10 ultrasonic transducer generates a megacycle center frequency ultrasonic pulse having a wavelength in the range of the average grain size (in the direction of ultrasound propagation) of a sputtering target specimen. The ultrasonic pulse is introduced into the specimen at an incident angle normal to the surface of the specimen. Due to interaction of the ultrasonic pulse with the texture of the specimen, backscattering 15 echoes are generated in a portion of the specimen located within the transducer focal zone. The backscatter region extends at least one grain layer beneath the specimen surface to a depth of several grain layers in thickness. The backscattering echoes propagate back to the transducer where the echoes are converted by the transducer into an electrical signal which is processed by a broad-band acquisition system. A 20 maximum amplitude value of the backscattering signal is extracted from the processed data and stored in a memory of the acquisition system for future data analysis. Data analysis is performed using data graphical representation in the form of a histogram of "occurrences versus amplitude" where the amplitude is plotted along the x axis while the occurrences (counts for certain amplitude values) are 25 plotted along the y axis. The histogram is compared with histograms for reference standards having known preferred crystallographic and grain orientation, grain size, and chemical composition.

Therefore, it is an object of the invention to provide a method of ultrasonic on-line texture characterization.

30

It is a further object of the invention to provide a method of on-line texture characterization including the step of generating an ultrasonic pulse with a wavelength in the range of the average grain size of a specimen material in the direction of ultrasound propagation.

It is yet another object of the invention to provide a method of ultrasonic on-line texture characterization including the step of detecting an ultrasonic backscattering signal generated by interaction of an initial ultrasonic pulse with specimen material texture.

5 A still further object of the invention is to provide a method of ultrasonic on-line texture characterization including the step of plotting the backscattering signal amplitude in the form of a histogram of "occurrences versus amplitude", and comparing the histogram with similar histograms for materials having known preferred crystallographic and grain orientation, grain size, and
10 chemical composition.

Other objects of the invention will be apparent from the following description, the accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Fig. 1 is a schematic diagram of a prior art method of ultrasonic texture analysis;

Fig. 1A is a schematic diagram showing the ultrasound echoes obtained by the prior art method shown in Fig. 1;

20 Fig. 2 is a schematic diagram of a method of ultrasonic on-line texture characterization in accordance with the invention;

Fig. 3 is an enlarged schematic view of the backscattering region of the sputtering target of Fig. 2 showing backscattering echoes propagating from grain boundaries;

25 Fig. 4 is a histogram of "occurrences versus amplitude" obtained according to the method of the invention for a relatively isotropic "random" texture;

Fig. 5 is an X-ray diffraction pole-figure proof for the data shown in Fig. 4;

30 Fig. 6 is a histogram of "occurrences versus amplitude" obtained according to the method of the invention for an anisotropic material having a strong <100> preferred crystallographic orientation:

Fig. 7 presents the X-ray diffraction pole-figure proof for the data shown in Fig. 6;

Fig. 8 is a histogram of "occurrences versus amplitude" obtained in accordance with the method of the invention for a <100> single crystal;

Fig. 9 is a plot of normalized intensity versus tilt angle alpha, <200> azimuthally averaged, for the sputtering target of Figs. 4 and 5;

Fig. 10 is a plot of normalized intensity versus tilt angle alpha, <200> azimuthally averaged, for the sputtering target of Figs. 6 and 7;

Fig. 11 is a plot of normalized intensity versus tilt angle alpha, <200> azimuthally averaged, for the <100> single crystal of Fig. 8; and

Fig. 12 shows the correlation between ultrasonic backscattering amplitude and degree of <200> preferred orientation for the sputtering targets and single crystal of Figs. 4 - 11.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning to Figs. 2 and 3, there may be seen schematic diagrams

15 illustrating the method of the instant invention. A single, short-duration, megahertz frequency range ultrasonic pulse 20, is generated by a focused ultrasonic transducer 22. The pulse 20 is directed at a material 24 such that the angle of incidence of the pulse 20 is normal to the surface 26 of the material 24. A backscattering signal 28 originates in a backscattering region 32. The backscattering region 32 is located 20 inside a transducer focal zone 34 and has a depth extending from at least one grain layer beneath the surface 26 to a depth of several grain layers.

Backscattering occurs as a result of acoustic impedance (i.e., ultrasound velocity) mismatch at grain boundaries of adjacent grains. Due to a limited number of grain boundaries along the ultrasound path inside the 25 backscattering region 32, the backscattering signal 28 experiences less signal volume averaging than the reflected ultrasonic signal of the prior art (Fig. 1). At a nearly resonant mode of ultrasound propagation (i.e., the ultrasound wavelength is in the range of average grain size), the statistics of identical wave phase shift at the grain boundaries inside the backscattering region 32 will depend on the degree of preferred 30 crystallographic orientation. The number of identical wave phase shifts increases with increasing degree of preferred crystallographic orientation. The increase in the number of identical phase shift occurrences is detected as an increase in the number of counts for identical backscattering amplitudes. As a result, a histogram of

"occurrences versus amplitude" tends to shrink in width and stretch in height with increasing kurtosis of the histogram (Fig. 6). In contrast, for materials having more isotropic texture, the histogram of backscattering signal amplitude is broader and shorter due to more random phase shift distribution (Fig. 4).

5 Turning now to Figs. 4 and 6, there may be seen histograms of backscattering signal amplitudes obtained in accordance with the method of the invention for two different material specimens. The first material specimen used to produce the histogram given in Fig. 4 is of an isotropic random crystallographic orientation. The Fig. 6 histogram results from ultrasonic analysis, in accordance with 10 the invention, of a strong <100> preferred crystallographic orientation.

In both cases, the specimen materials comprise aluminum-0.5 weight percent 15 copper alloy having equivalent-axed grain texture (crystallographic orientation) and grain sizes in the range of 0.26 millimeter to 0.38 millimeter. The ultrasonic transducer 22 used to obtain the histograms is a 15 megahertz spherical focalization 20 transducer. The region for backscattering signal monitoring is specified by focusing the transducer on a flat bottom hole of 0.1 millimeter diameter located at a distance of two millimeters under the surface of the specimen material. Comparing Fig. 6 with Fig. 4, it may be seen that the less textured material of Fig. 6 exhibits a narrower and taller or more elongated histogram of backscattering signal amplitude than the 25 material having more random texture as shown in Fig. 4. The X-ray diffraction pole-figures of Figs. 5 and 7 confirm the findings of the observed differences in the preferred crystallographic orientations of the two specimen materials. It should be noted that the effects of isolated, minute flaws on the histograms can be discarded or ignored if the total number of data points acquired exceeds the number of flaw-related data points by three to five orders of magnitude.

By way of comparison, the histogram for a single crystal of Al-0.5 30 wt% Cu alloy having a crystallographic orientation of <100> is shown in Fig. 8. The histogram of Fig. 8 was also obtained using a 15 megahertz spherical focalization transducer focused on a flat bottom hole of 0.1 millimeter diameter located at a distance of two millimeters beneath the surface of the crystal. The histogram shows an amplitude variation for the single crystal of about 4.7%, and a peak of about 2,716 occurrences.

Graphs of normalized intensity versus tilt angle alpha in degrees for a <200> azimuthally averaged X-ray beam for each of the samples of Figs. 4, 6, and 8, may be seen in Figs. 9, 10, and 11, respectively. Figure 12 shows a plot of the normalized ultrasonic backscattering amplitudes versus the degree of preferred 5 <200> intensity normalized (azimuthally averaged) for each of the three sample specimens.

The plot in Fig. 12 shows that there is a linear correlation between the results obtained from the instant texture characterization analysis by ultrasonic backscattering means and a conventional X-ray diffraction pole-figure analysis 10 method. For example, point 202 in Fig. 12 shows the normalized intensities for both the ultrasonic detection means (y-axis) and x-ray diffraction methods (x-axis) as applied to the isotropic random texture specimen with point 204 representing the x, y coordinate intensities found for the strong <100> preferred orientation sample. Point 206 represents the ultrasonic and x-ray diffraction intensities for the single 15 crystal material tested. Thus, the instant method of ultrasonic on-line texture characterization analysis yields good results when compared with standard out-of-line measurement techniques since there is a clear linear relationship between the two methods.

It is to be noted that the ultrasonic pulse to be applied to the sputter 20 target may be applied through a fluid medium such as air or water. Presently, it is preferred to place the sample in a water immersion tank to thereby apply the pulse through water. Typically, the transducer will be located at normal incidence to the specimen surface.

The pulse or burst of MHz- range frequency electrical signal is 25 generated by an electronic pulser tuned to the frequency range of the ultrasonic transducer (11-18.5 MHz). This signal is converted by the transducer into an ultrasound pulse. The ultrasound pulse propagates through the water (which is a couplant) at a normal incidence to the specimen surface.

As a result of the interaction of the ultrasonic pulse with the exposed 30 volume of the specimen (approximately 5 mm deep into the specimen measured from the top surface) part of the ultrasonic energy is scattered back to the transducer in the form of an echo.

The exposed area is situated inside the transducer focal zone (-6 dB).

When the echo arrives, the transducer electronically switches from an electronic transmitter to a gated electronic receiver. The echo is received at the transducer about 60 microseconds after the pulse is sent.

5 The returned RF signal (the ultrasonic echo) is captured inside the gate of a low noise gated preamplifier. The pre-amplified RF echo is passed to the low noise linear amplifier.

10 The echo acquisition system includes: the low noise gated preamplifier; the low noise linear amplifier with a set of calibrated attenuators; and a 12-bit ADC (2,44 mV/bit) and a PC equipped with a printer.

The linearly amplified analog RF echo signal is digitized by the 12-bit ADC (2,44 mV/bit) and passed in digital form to the PC. The maximum value of the digitized RF signal is stored in the memory of the PC software. This maximum value is used for texture analysis.

15 The texture analysis device shown in Fig. 2 uses an immersion tank filled with DI water. It is equipped with a mechanical X-Y scanner, electronic pulser-receiver instrument and transducer assembly mechanically attached to the X-Y scanner. The mechanical X-Y scanner is controlled by a PC based electronic controller. The X-Y scanning unit performs a meander-like stepwise motion with 20 short steps in the X direction and longer steps in the Y direction. Data acquisition steps in both X and Y directions were chosen to equal 0.8 mm to provide a detection of 0.1 mm flat bottom hole at detection level (9-6 dB) without exposure area overlapping.

25 The preferred transducer is sold by Panametrics, USA under the model V 319 designation. This is a high resolution piezoelectric transducer having a focalization distance of 51 mm and 12.5 mm in diameter with a center frequency of 15 MHz and 7.2 MHz bandwidth (-6 dB).

In detecting the backscatter echo, software available from Structural Diagnostics, Inc. under the designation SDI-5311 can be used.

30 Before testing, the specimen surface should be prepared via diamond cutting or the like. Usually, the texture characterization is performed for the entire area of the target, usually 7.5 in. x 7.5 in. For texture analysis, about 50,000 - 500,000 raw data points are analyzed. The velocity of the ultrasonic pulses

propagating from the target is commonly on the order of about $6.29\text{--}6.35 \times 10^{-1}$ cm/microsecond.

While the method herein described, and the form of apparatus for carrying this method into effect, constitutes a preferred embodiment of this

5 invention, it is to be understood that the invention is not limited to this precise method and form of apparatus, and that changes may be made in either without departing from the scope of the invention, which is defined in the appended claims.

--CLAIMS--

1. A method of ultrasonic texture characterization analysis comprising the steps of:
 - (a) irradiating a target with sonic energy;
 - 5 (b) detecting echoes of said sonic energy reflected from said target;
 - (c) forming a histogram of the number of occurrences of said echoes versus the amplitude of said echoes; and
 - (d) comparing said histogram with reference histograms of
- 10 specimens having known texture characteristics.
2. Method as recited in claim 1 wherein said target comprises a generally planar surface and wherein said sonic energy is irradiated onto said target at an incident angle of about 90° relative to said planar surface.
3. Method as recited in claim 2 further comprising irradiating said target with beams of sonic energy focused beneath said planar surface.
4. Method as recited in claim 3 wherein said target comprises a metal or metal alloy having a multiplicity of grain layers distributed through the thickness of said target. said step of irradiating comprising focusing said beams of sonic energy in a zone located beneath said planar surface and extending to a depth defined by a
5 plurality of grain layers.
5. A method of non-destructively testing a sputtering target having a front wall and comprising sputtering material having grain boundaries and an approximately known grain size, said method comprising the steps of:
 - (1) directing a pulsed beam of sonic energy from a transmission
 - 5 point toward said target, said sonic energy having a frequency such that its wavelength in said target is substantially equal to said known grain diameter and said beam being directed such that a portion thereof passes through said front wall, reflects off said grain boundaries, passes again through said front wall and travels to a reception point having a predetermined position relative to said transmission point;

10 (2) sensing said beam portion at said reception point and generating a corresponding sensing signal; and
(3) determining for said sensing signal a histogram of the number of occurrences of said sensing signal at a predetermined amplitude level.

6. A method of determining the degree of preferred crystallographic orientation of a sputtering target having an approximately known nominal grain size and grain boundaries comprising the steps of:
(a) irradiating said sputtering target with an ultrasonic pulse
5 having a wavelength, in the sputtering target, in the range of said nominal grain size of said sputtering target;
(b) detecting backscattering echoes generated by said ultrasonic pulse interacting with said grain boundaries in said sputtering target;
(c) generating an electrical signal representative of said detected
10 backscattering echoes;
(d) determining the number of occurrences of said detected backscattering echoes for predetermined ranges of amplitudes of said detected backscattering echoes;
(e) producing a histogram of said number of occurrences versus
15 said predetermined ranges of amplitudes for said sputtering target; and
(f) comparing said histogram with reference histograms for reference sputtering targets having known preferred crystallographic orientations.

7. An express ultrasonic method for on-line texture characterization which provides a control for the texture variation in production environment, consists of a pulse-echo method incorporated into an ultrasonic C-scanning process, wherein a megacycle center frequency ultrasonic pulse generated by a broad-band focused
5 ultrasonic transducer is introduced at a normal incidence into material wherein the ultrasonic signal due to an interaction with material texture scatters back to the transducer in the form of a backscattering echo which is further converted by the transducer into an electrical signal and processed by a broad-band acquisition system, extracting and storing the backscattering signal amplitude, the distinct form of this
10 method comprising:

(a) the generation of the initial ultrasonic pulse with a wavelength in the range of the average grain size in the direction of ultrasound propagation;

(b) the backscattering signal is collected from the region of several grain layers thick located inside the transducer focal zone;

15 (c) the backscattering signal is collected from the region located at the distance, at least, of one grain layer underneath the surface.

8. The method as in claim 7 wherein said amplitude of said backscattering signal is graphically treated in a form of histogram: "Occurrences versus Amplitude" where the amplitude is plotted along the X-axis while the occurrences - along the Y-axis.

9. A method for non-destructively testing a sputter target, said method comprising the steps of:

(a) directing a mechanical wave normally onto a surface of said sputter target, said mechanical wave including a component having a selected 5 wavelength in the sputter target on the order of an average grain size of said target;

(b) detecting backscattered waves from said target having said selected frequencies;

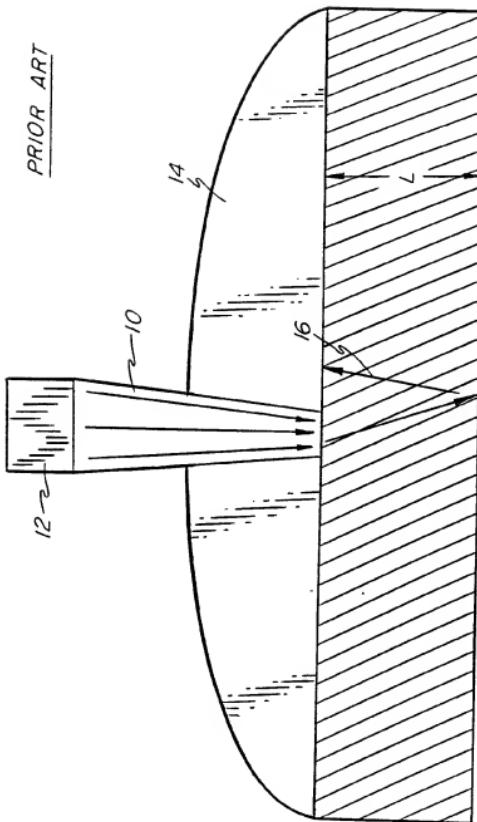
(c) relating amplitudes of the backscattered waves with detected 10 occurrences of said backscattered waves having said amplitudes so as to obtain a characterization of a grain texture of said sputter target.

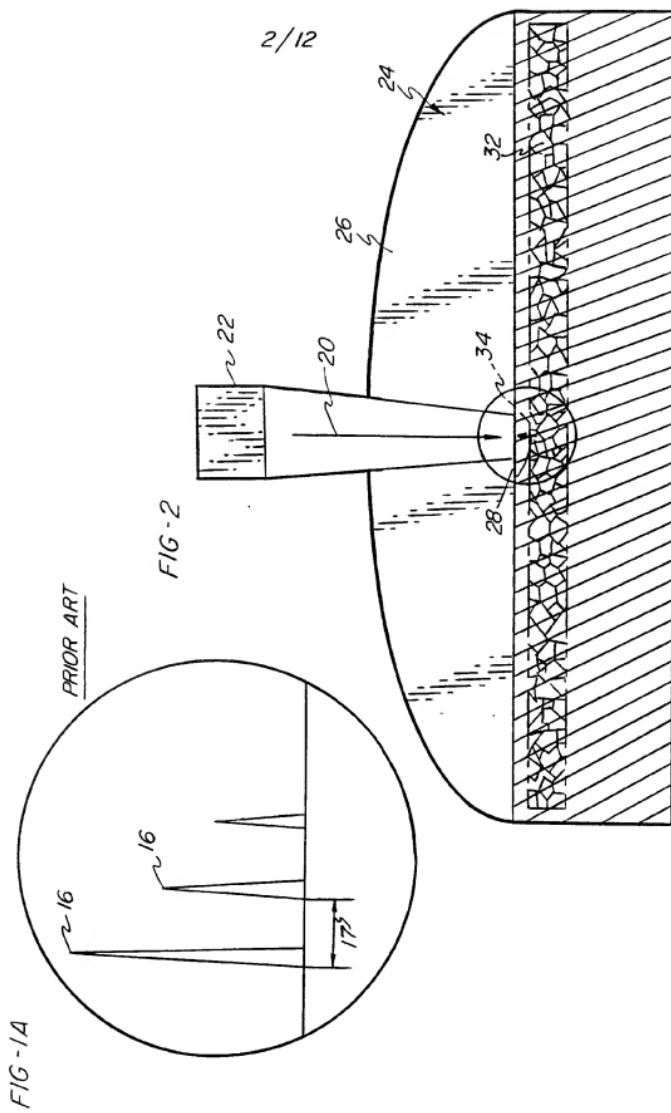
10. The method as recited in claim 9 wherein said step (c) includes generating a digital electrical signal relating said amplitudes with said detected occurrences.

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PRIOR ART

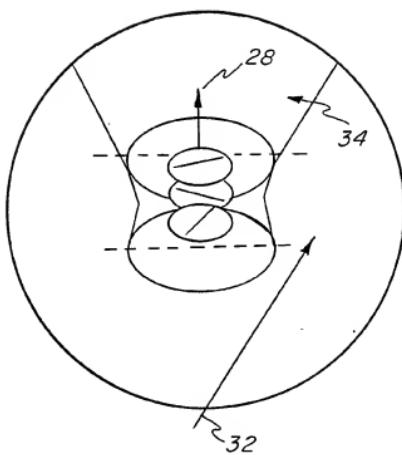
FIG. 1





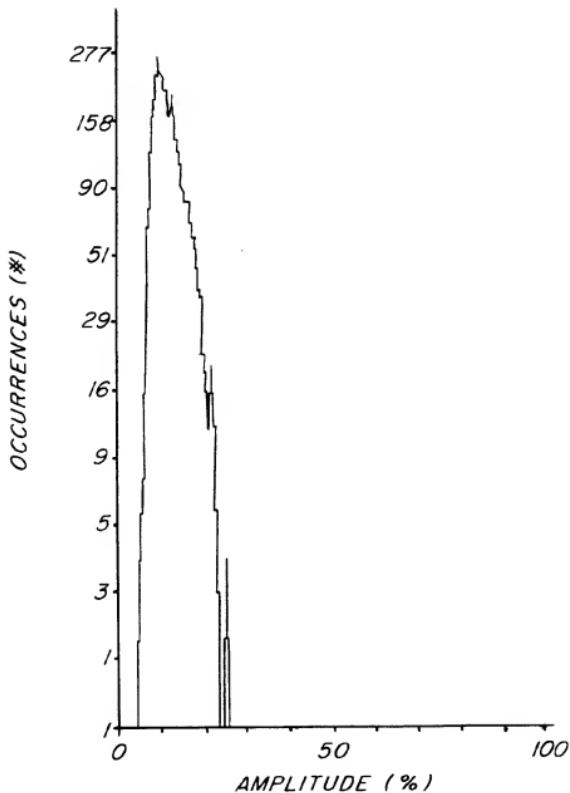
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FIG - 3



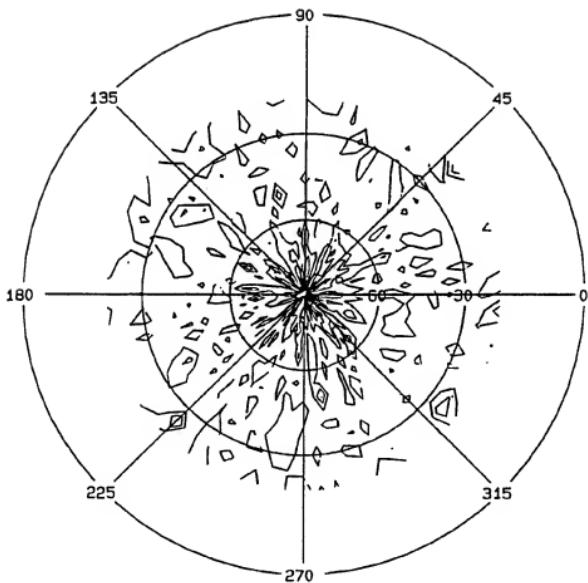
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FIG. 4



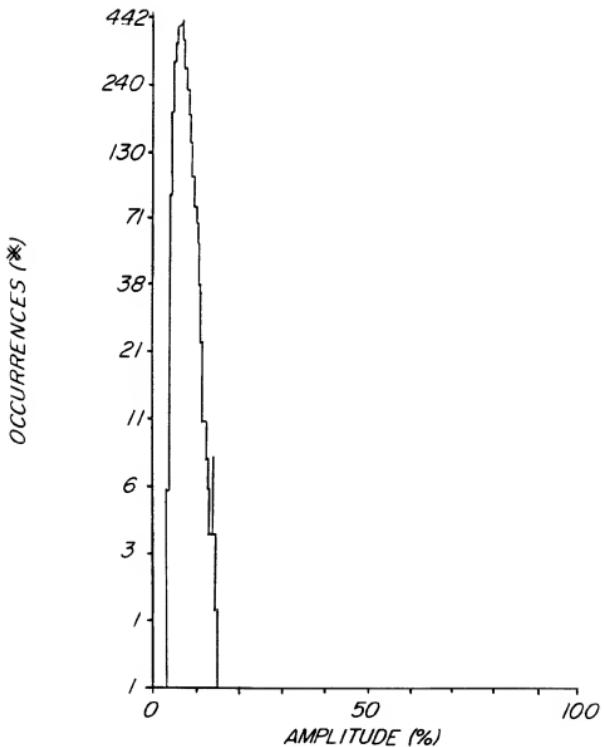
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FIG - 5



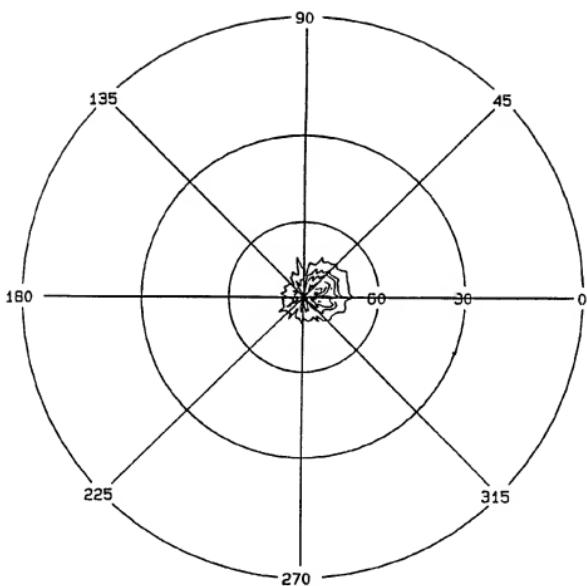
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FIG. 6



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FIG -7



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FIG -8

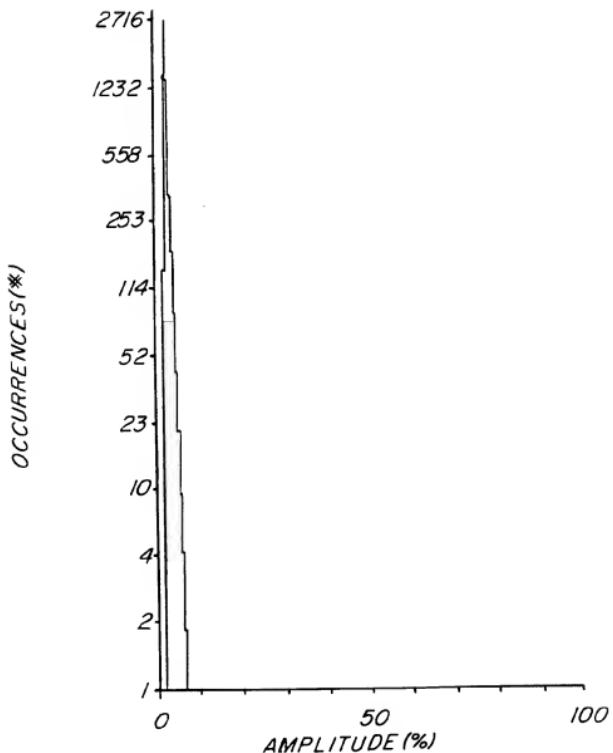
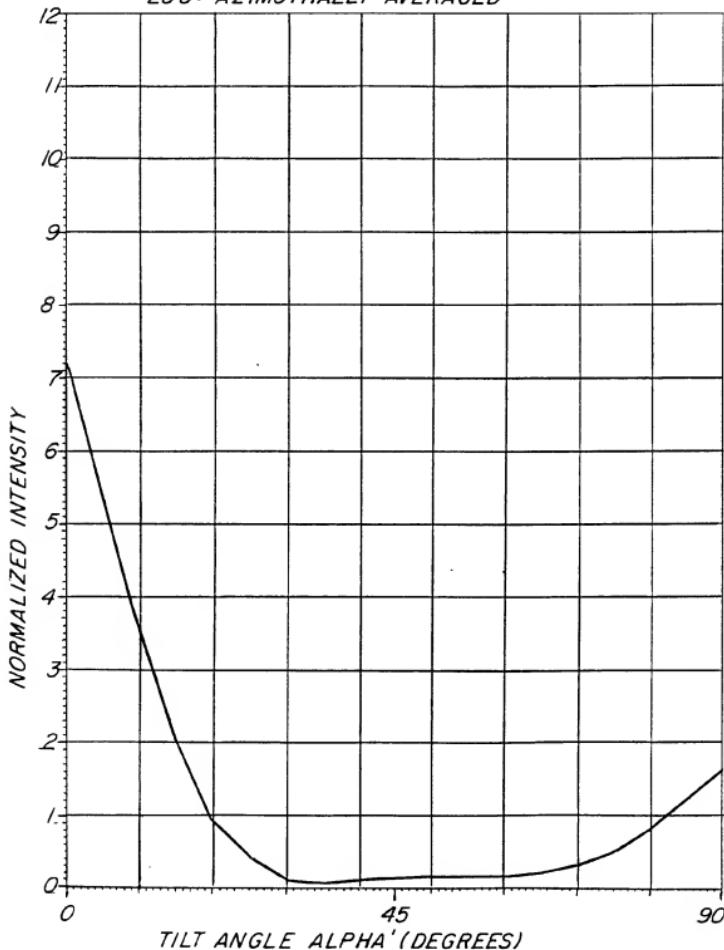


FIG - 9

9/12

<200> AZIMUTHALLY AVERAGED



10/12

FIG. 10

<200> AZIMUTHALLY AVERAGED

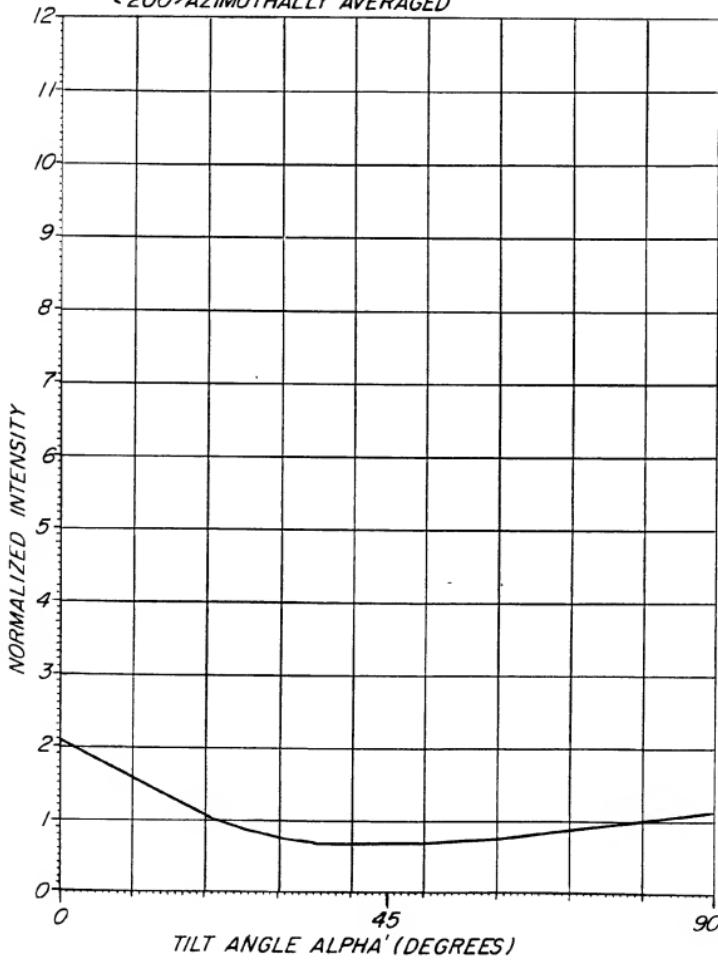
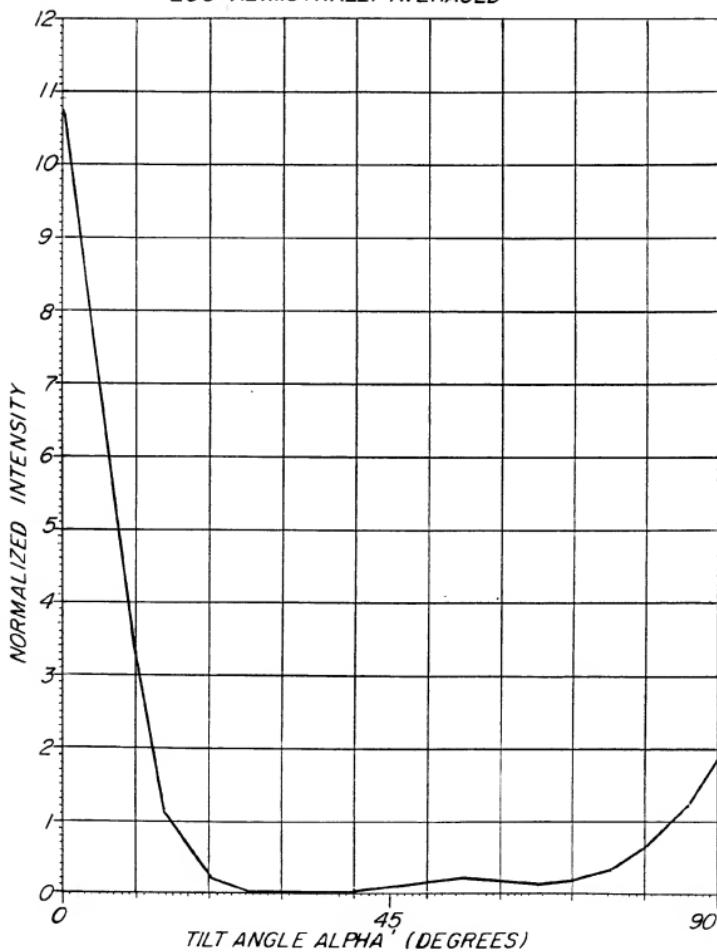


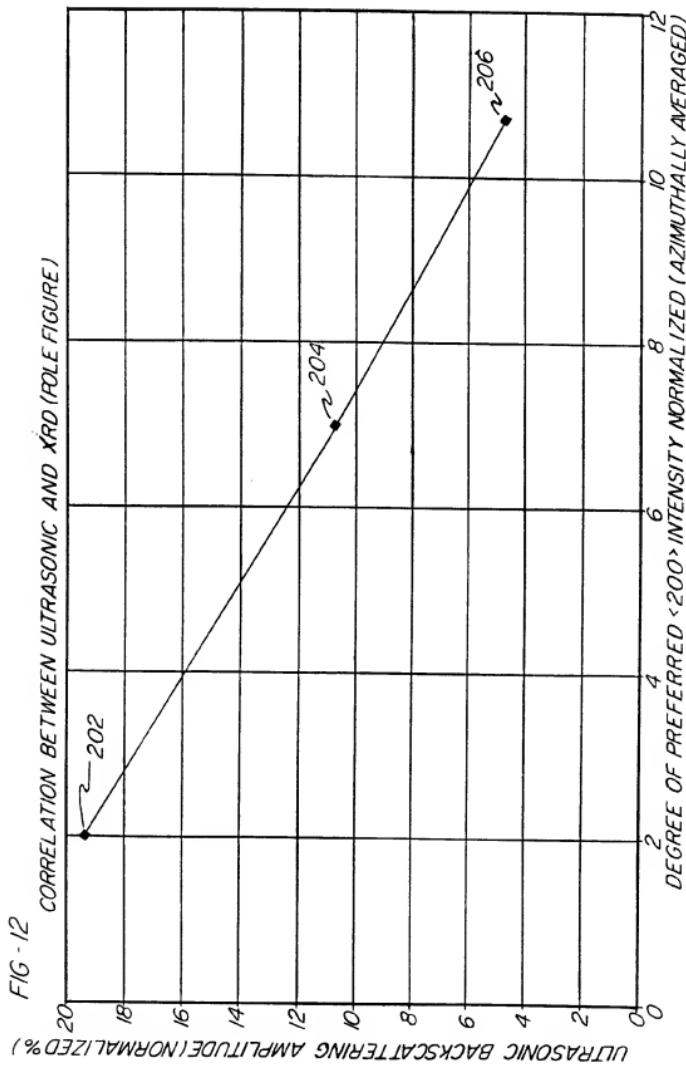
FIG -11

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<200> AZIMUTHALLY AVERAGED



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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/00091

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01N 29/06, 29/10; G01H 5/00
US CL :73/602, 620, 627

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 73/597, 598, 599, 600, 602, 620, 627, 629

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS: acoustic, ultrasonic, ultrasound, backscatter, backscattering, texture, histogram, sputtering

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
A, P	US 5,804,727 A (LU ET AL.) 08 September 1998 (08/09/1998) see abstract, Figures, and column 3 lines 20-55.	1-10
A	US 5,631,424 A (NIETERS ET AL.) 20 May 1997 (20/05/1997) see abstract, Figures, and column 1 line 65 - column 2 line 51.	1-10
A	US 5,406,850 A (BOUCHARD ET AL.) 18 April 1995 (18/04/1995), see abstract, Figures, and column 1 line 50 - column 2 line 11.	1-10
A	US 5,404,754 A (WANG) 11 April 1995 (11/04/1995) see abstract, Figures, and column 2 line 1 - column 3 line 20.	1-10

 Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:	*T*	later document published after the international filing date or priority date and not in conflict with the application but used to understand the principle or theory underlying the invention
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International application No.
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MASON, W.P. and McSKIMIN, H.J. Energy Losses of Sound Waves in Metals Due to Scattering and Diffusion, Journal of Applied Physics, October, 1948, Vol. 19, pages 940-946, especially see the abstract on page 940.	1-10